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Published in:
International Journal of Disaster Risk Reduction

DOI:
10.1016/j.ijdrr.2019.101139

Publication date:
2019

Flood Risk Management in Sponge Cities: The Role of Integrated Simulation and 3D Visualization

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Abstract: The Sponge City concept has been promoted as a major programme of work to address increasing flood risk in urban areas, in combination with wider benefits for water resources and urban renewal. However, realization of the concept requires collaborative engagement with a wide range of professionals and with affected communities. Visualization can play an important role in this process. In this research, a sponge city flood simulation and forecasting system has been built which combines hydrological data, topographic data, GIS data and hydrodynamic models in real-time and interactive display in a three-dimensional environment. Actual and design flood events in a pilot sponge city have been simulated. The validation results show that the simulated urban water accumulation process is consistent with the actual monitoring data. Use of advanced virtual reality technology can enable simulations to be placed in the wider design context including enhanced awareness of multiple functions of urban ecosystems. This procedure can therefore reduce the information communication gap and encourage innovation regarding low impact development required for sponge city construction.

Keywords: Sponge City; Flood Risk Management; 3D Visualization; GIS; Low impact development

1. Introduction

During recent decades, China has undergone a major and unprecedented urbanization that has been unparalleled in global terms. This transition has brought significant environmental challenges, including for water resources and flood risk management, for which more sustainable outcomes are now being sought. In terms of disaster risk, unconstrained urbanization can significantly increase both exposure and vulnerability to natural hazards, especially for fast-onset extreme events such as flooding through modification of hydrological pathways due to soil sealing and use of impermeable surfaces. This risk is likely to be further exacerbated by changes in the intensity and magnitude of extreme events due to climate change.

In December 2013, President Xi Jinping announced a national plan to reduce flooding in China's cities, as a response to the increased frequency of serious urban flooding in the country. The main aim was to transform current urban areas into "sponge cities" by upgrading the existing urban drainage infrastructure and utilising natural systems to improve water retention, infiltration and drainage. "Sponge City" is a new concept of integrated urban stormwater management, which enables Chinese cities to have good resilience in adapting to environmental changes and coping with natural disasters [1]. The sponge city concept includes water bodies such as rivers, lakes and ponds, as well as supporting urban facilities such as green spaces, gardens and permeable road surfaces. Rainwater is infiltrated, purified, stored and reused, with residual flows routed through a network of pipes and pumping stations, to effectively raise the design standard of urban drainage system and reduce the flood risk in the city. Currently, there are 30 pilot cities in China with specific water-related targets on facilitating natural pathways for interception, infiltration and purification in sponge cities. The aim of the programme has now also been extended to incorporate a wider range of multiple benefits in addition to flood risk management, and to include planning for climate change.

The sponge city initiative was inspired by low impact developments (LID) elsewhere in the world that would be scaled and transferred into the Chinese urban context. These existing developments include LID in the US [2], water sensitive urban design (WSUD) in Australia[3], sustainable urban drainage systems (SUDS) in the UK[4], and integrated urban water management systems in Denmark and Sweden[5][6]. For example, in Malmö, different storm-water collection networks as well as large-scale open storm-water handling implementations are already present in forms such as ponds, wetlands, swales, canals, detention lakes, and green roofs[5]. Copenhagen is mainly dominated by fully developed sewer systems[6] but recent extreme events have shown a need to redesign the drainage system to better adapt to extreme rainfalls; this goal is being achieved through modifications to the connectivity of the combined sewer network and integrated use of low sensitivity surfaces coinciding with public spaces (e.g. parks, sport fields and open space for temporary storage of storm water)[5].

There are numerous major challenges for sponge city development with regarding to technical/physical, legal/regulatory, financial, and community/institutional engagement at the local, regional and national levels[7]. A focus only upon the technical challenge is therefore insufficient to deliver the ultimate objectives, requiring design standards and code to be aligned with monitoring/evaluation, education/training and effective operation/maintenance. At the core of the concept is the enhanced use of natural infrastructure through eco-engineering in local planning, regulations and projects to help reduce flood exposure. However, eco-engineering approaches for risk reduction represent a step change from conventional engineering techniques and their successful application requires integration of science, design and policy based upon agreed decision outcomes[8]. Hence, although progress in sustainable urban water management is influenced by technological innovations, a key challenge has been identified in aligning sponge city initiative projects with infrastructure and urban renovation portfolios[9]. Consequently, the major investment in sponge city construction programmes requires equivalent emphasis on stakeholder engagement and public perception in order to incorporate community opinions on current construction plan and future flood risk management. Researchers have therefore highlighted important knowledge gaps in current initiatives including requirements for improved inter-disciplinary approaches, a comprehensive design framework, and improved application of information technology [10].

The scale of ambition and the challenges involved in converting a visionary concept into a practical reality suggest there is a valuable role for visualization in the Sponge Cities programme. This is further emphasized by the additional complications involved when implementing the concept into specific local contexts, each with their distinctive biophysical and socioeconomic features. Traditional landscape architecture visuals are often employed to convey key aspects of the sponge city concept (e.g. permeable surfaces and associated greenspace) but these do not facilitate an interactive or immersive engagement with the proposed design features. In other contexts, innovative use of computer-based visualization and Virtual Reality (VR) technology has been shown to encourage greater engagement and awareness of landscape design challenges amongst diverse participants[11][12], further highlighting our rationale for investigating its application in meeting the design challenges of sponge cities. Most notably, the additional realism of a 3D application may also help avoid misunderstandings that occur between the design teams and stakeholders when using 2D illustrations that typically leads to the need for re-design and reworking during the design phase.

In flood risk management, the main bottleneck to risk reduction is usually not the lack of information, but rather how this information is communicated and perceived[13]. 3D visualization and associated tools can therefore have benefits which could support delivery of the types of aspirations or regulatory requirements in public policies which relate to planning and development. Furthermore, an important requirement in advancing good design practice is understanding how sponge cities function during extreme events and not just in normal conditions. This functioning not only refers to the storage of water for flood risk reduction but also associated implications for the wider range of benefits that the design might provide, extending also to the visual and aesthetic aspects which may also be perceived as crucially important by local people and stakeholders (e.g.

businesses)[14]. This identifies the further advantages of combining visualization with simulation modelling to explore the expected changes during a particular event, such as a design flood event. Following this rationale, a combined simulation-visualization platform can become an important shared learning tool, meaning planner, decision maker and public can get involved in developing a shared vision for the sponge city concept in a collaborative format.

2. Flood Simulation

Flood simulation and modelling can be used to provide relevant information on the dynamics of flood risk at a location and therefore the consequences for people living there. Simulating and modelling flood hazard are rapidly developing fields in hydrology[15]. Topographic data are crucial for flood inundation modelling and it is best to use recent and highly accurate topographic data. Current methods of flood hazard warning include numerical simulation[16][17][18][19], remote sensing approaches[20][21], rainfall data estimation[22] and flood simulation based on geographic information system (GIS) [23][24]. Although these methods can solve some important problems, there are still two disadvantages in terms of risk communication: i) the flood prevention system is constructed in 2D environments other than 3D real world; ii) flood risk forecasts are mainly based on the analysis of historical data.

There are increasing requirements for developing efficient flood warning systems for decision making and risk management. Flood warning systems must be reliable and designed to operate during the most severe floods. A web-based flood forecasting system can be used to carry out real-time rainfall data conversion, model-driven hydrologic forecasting, model calibration, precipitation forecasting, and flood analysis [25]. However, the effectiveness of this system can be compromised by deficiencies of hydraulic flood spreading procedures as the extreme event progresses [26]. Remotely sensed precipitation data and hydrologic modelling are used to monitor flooding in regions that regularly experience extreme precipitation and flood events[27], but this needs an offline process for data collection and also appears less efficient for real time implementation. The ability of high-resolution TerraSAR-X synthetic aperture radar (SAR) data to detect flooded regions in urban areas with a semiautomatic algorithm for the detection of floodwater in urban areas has been validated using aerial photographs[28], but the main drawback of this approach is its poor display performance due to its 2D processing. A European flood forecasting system has been developed for determining what flood forecast skill can be achieved for given basins, meteorological events and prediction products[29]. It consists of several components: i) global numerical weather prediction models; ii) regional numerical weather prediction model; iii) a catchment hydrology model; iv) flood inundation model. The major challenge of this approach is dealing with uncertainty in such a complex system of linked numerical codes and database, and challenges have been identified in applying such a system in developing countries with limited historical data [26], especially in locations where flood vulnerability is an increasing concern [30].

The present study aims to show how a combined simulation-visualization approach can enhance decision support by incorporating model uncertainty analysis, computationally efficient real-time data assimilation/forecasting algorithms, 2D inundation modelling[31], and 3D data visualization[32]. Previous work has shown that this requires a consistent approach to data integration and model development across the suite of tools and techniques[33]. In[34], an early flood warning system has been developed which is useful to provide timely and correct information for flash flood conditions and to facilitate anticipatory adaptation actions to reduce risks, including to both reduce risk exposure and vulnerability. It combines offline hydrologic analysis and online flood alert application. Hydrologic simulation was performed using HEC-HMS for runoff forecasting with a client-server programme used to visualize the real time flood condition and to deliver the early warning message.

3. Case Study of Xixian new area

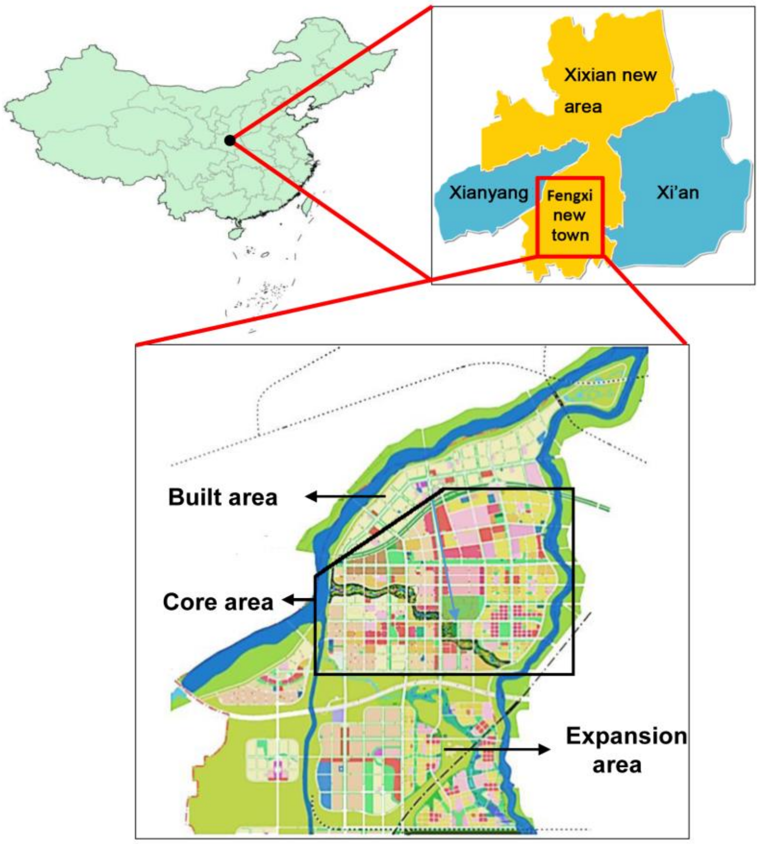


Fig.1. Pilot area location: Fengxi new town in Xixian new area of China

Xixian new area is China's seventh state-level new area and included in the first batch of national sponge city construction pilot cities[35]. There are five new towns in Xixian new area which covers 882 km^2. The current population is 0.96 million and planned to be 2.36 million by 2020. The pilot area of sponge city construction in Xixian new area is the core area of Fengxi new town. It starts from the Xibao highway in the south, to the Tongyi road in the north, to the Wei River in the west, and to Hanfei Road in the east, with a total area of 22.5 km^2. The locations of the pilot and core area are shown in Fig.1.

The main goal of the plan is to design compact, ecologically-based, low carbon, and harmonious garden city including forest protection system, country parks, mitigation of heat island effect, public health facilities and social welfare system. The sponge city programme in Xixian new area is designed to utilize natural systems (e.g. rain garden, green roof, permeable pavement, underground storage tank) to improve urban ecosystem functions and reduce urban flooding.

The construction of Sponge City consists of LID technology, drainage system and excessive rainwater retention system. The Sponge City plan aims to co-ordinate and integrate these three major design systems through three main types of LID in the Xixian new area: bioretention, permeable/porous pavement system and green roof or ecological roof (Ecoroof).

According to the design characteristics of roads in Xixian new area, the LID measures along both sides of the pilot area are mainly rainwater gardens and ecologically-integrated vegetated ditch. The test site in Xixian has implemented permeable paving on the sidewalks of the Qinhuang Road and the Kang-ding-he-yuan residential area. The hydrological role of Permeable/Porous Pavement System (PPS) is to enhance the infiltration of rainwater, reduce impervious area, and to improve water quality through interception and reduced runoff of pollutants. Green roof is also very important to LID by using vegetated roofs to intercept rainwater, and at the same time achieving other energy saving functions, such as reducing the heat island effect and lowering the city temperature through evapotranspiration processes. Xixian new area has adopted a green roof design in the western cloud valley.

4. Methodology

The framework used for the development of a 3D model and simulation of design and actual flood in pilot sponge city brings together the design of LID (e.g. green roof and rain garden), compilation into a model of the site, design and representation of 2D flood events within an immersive 3D environment, implementation as tools for flood risk management, and user involvement in stakeholder workshop (Fig.2).

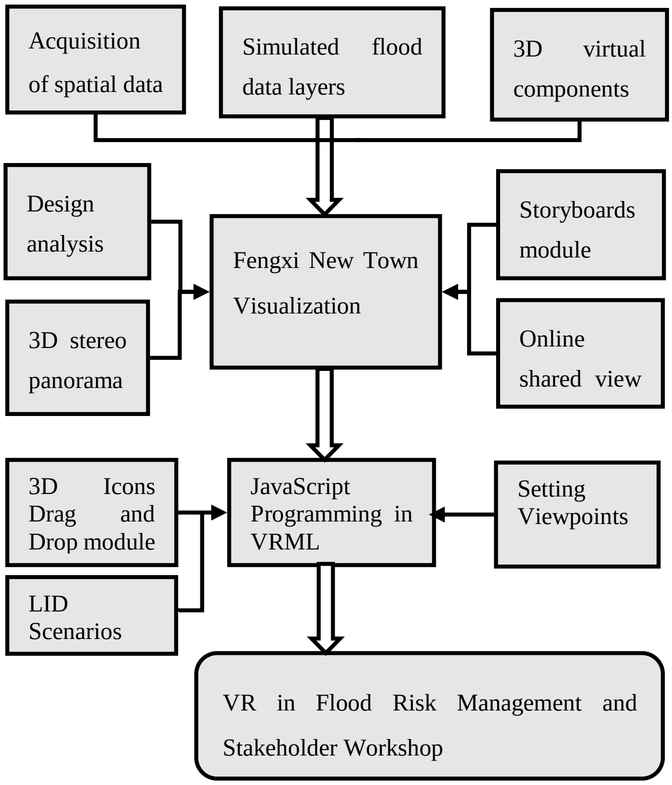


Fig.2. Framework for the development of the 3D model and simulation of design and actual flood in pilot sponge city with LID scenarios.

The tools used in the development and implementation of the 3D model were PC-based, enabling the incorporation of interactive functionality for manipulating features in such models. Inputs comprise spatial data and associated imagery, simulated flood data layers, and 3D virtual components. The main part of the system consists of Fengxi new town visualization with five interactive modules, featuring LID scenarios in VR environment. The model is then exported into a viewer (Octaga) in which the functionality is coded in JavaScript. The VR experience is used to communicate flood risk and therefore provides a collaborative platform to enhance flood resilience and understand co-benefits from sponge city design features.

4.1 Urban Flood Simulation Model

The numerical model that integrates hydrological and hydrodynamic processes has been developed to simulate the rain and flood process in the study area. This model uses the Godunov-type finite volume method and applies the second-order algorithm of the second-order MUSCL (Monotonic Upwind Scheme for Conservation Laws) method to strictly maintain the conservation of matter and robustly solve the discontinuity problem[36]. Water and momentum flux are calculated by the Harten-Lax-van Leer-contact (HLLC) approximate Riemann solver with the contact wave restored[37]. The bottom slope source term is processed by previous proposed flux method applied to a complex grid[38]. The friction resistance is calculated using a semi-implicit method with good stability, and the time is advanced using the two-step Runge-Kuta methods[39]. The use of GPU (Graphics Processing Unit) parallel computing technology to accelerate the calculation process can achieve large-scale computing on a single machine[40]. The model has high accuracy and computational efficiency, and is suitable for large-scale and complex urban storm-water process simulations. It has been previously validated[40] by a comparative analysis of simulated and measured data from a small watershed. The model used an open boundary during the simulation of urban storm floods. There was no accumulated water on the initial surface, and assuming soil saturation, the infiltration rate did not change over time, with the courant number (CFL) set to 0.5. The simulation was carried out for 5 hours. The accumulation of standing water in the study area under various design storm conditions was then obtained.

4.1.1 Flood Simulation and Model Validation

For the purpose of evaluating the computational efficiency and accuracy of the flood model, some typical residential districts in Xixian new area of Shanxi Province were selected as study sites, located between Xi'an and Xianyang City built-up areas (Fig.3(a)). The existing architectures are mainly residential buildings and school houses. The study area is located within a temperate continental monsoon climate zone. The average annual rainfall precipitation is about 520 mm, of which the precipitation from July to September accounts for about 50% of the annual rainfall, and the summer rainfall is mostly in the form of heavy rain, which has previously caused natural disasters such as urban floods. The model uses as input the measured rainfall and underlying surface data to simulate the urban pluvial flooding on the main street of the study area and compare it with the actual monitoring data to verify the model.

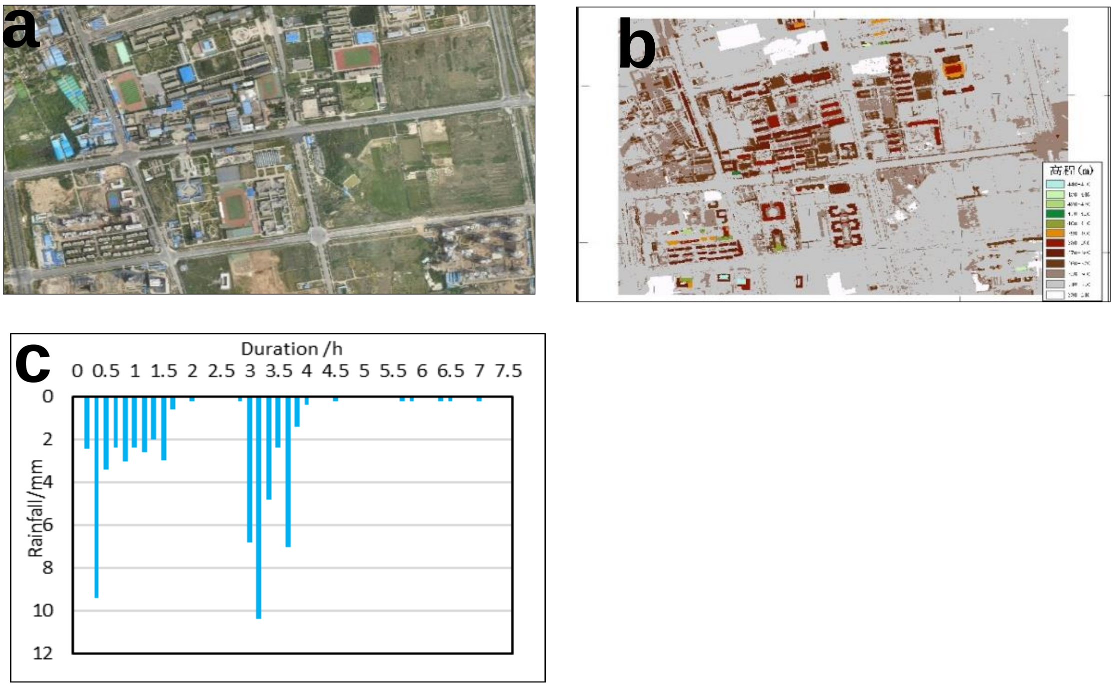


Fig.3. (a) Orthophoto map of the study area; (b) Digital elevation map of the study area; (c) Measured rainfall in 25th August 2016

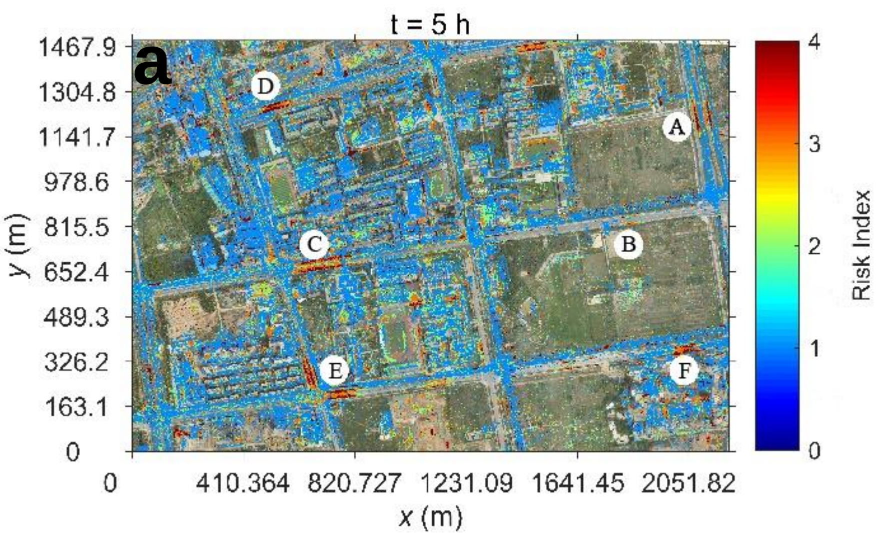
The model input data is divided into four parts: rainfall data, topographic data, infiltration data, and land use data. The observed rainfall data are provided by the weather station at No. 10 Building of Western cloud valley in Xixian New Area on August 25, 2016. The rainfall was of the double-peak type with a peak rainfall intensity at 3.1 hours, and lasted 7 hours, with a cumulative rainfall of 66 mm; the rainfall return period was a one in 50-year event at this location. Specific model input parameters are shown in Fig.3 and Table 1.

Table 1 Underlay surface properties and Manning Coefficient

Land use Classification	**Permeability**	**Manning Coefficient**
Residential（16%）	80%	0.015
Traffic Land（32%）	0	0.014
Bare land（18%）	100%	0.03
Forest Land（17%）	100%	0.2
Grass Land（17%）	100%	0.06

Model calculations use open boundaries with no inflows around. The calculation process was performed using the courant number (CFL) of 0.5 to simulate the water accumulation process from the beginning to 8 hours rainfall.

The simulation uses a microcomputer equipped with an NVIDIA GeForce GTX 1080 graphics card. The single-precision floating-point (32-bit) computing capability is 9 TFlops/s. Since this video card is positioned as a game card, the actual double-precision floating-point (64-bit) operation capability is less than 1/32 of the single-precision operation capability, and the model calculation is shared at 45169 s (12.5 h). In order to solve this problem, the model is also running on a computer equipped with a professional graphics card Tesla K20 with double-precision floating-point performance up to 1.17 TFlops/s. Fig.4(a) shows the process of water accumulation in this simulation.



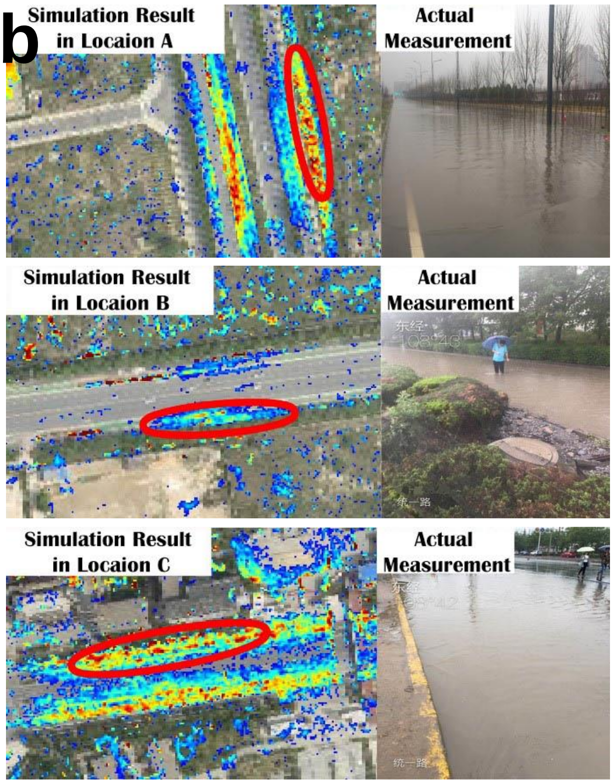


Fig.4. (a) Urban flood risk map for the study area; (b) Comparison between simulated water accumulation and measured water accumulation

In Fig.4(b), three inundation regions which are more severely affected by urban flood are marked and compared with the actual measurement records. From Fig.4(b) and Table 2, it can be seen that the location of the simulated water is consistent with the location of the urban pluvial flooding (three locations), and the degree of accumulated water at each point is similar to the measured data. The average relative error of the area of accumulated water is 3.44%. The average relative error of water depth within the reservoir is 16.49%. The comparison results show that the simulated urban water accumulation process is consistent with the actual monitoring process.

Table 2 Comparing simulated water level with actual situation

Location of waterlogging	**Area of waterlogging /m^2 （simulation result / actual measurement）**	**Water depth of inundation area /cm （simulation result / actual measurement）**
A. Baimahe Road North Section	1621.51 / >1600	55 / >50
B.Tongyi Road East Section	464.21 / >480	35 / >30
C. Tongyi Road West Section	1566.12 / >1600	40 / >40

4.1.2 Design Rainstorm Event Simulation

Using rainfall data at Xianyang hydrological station from 1981 to 2016, the simulation model solved the following rainstorm intensity equation of the "China Outdoor Drainage Design Code" (GB50014-2006) [41] for Fengxi new town in Xixian new area.

$$q = \frac{1239.91 \times (1 + 1.971 \times \lg p)}{(t + 7.4246)^{0.8124}} \tag{1}$$

Where: q is the storm intensity (unit: L/(s·hm^2), p is the return period (unit: a), the current value range is 2a~200a; t is the rainfall duration (unit: min), with the value range between 1 to 1440 min.

Fig.5 shows the two hours design rainstorm rainfall with the return period of 50 years.

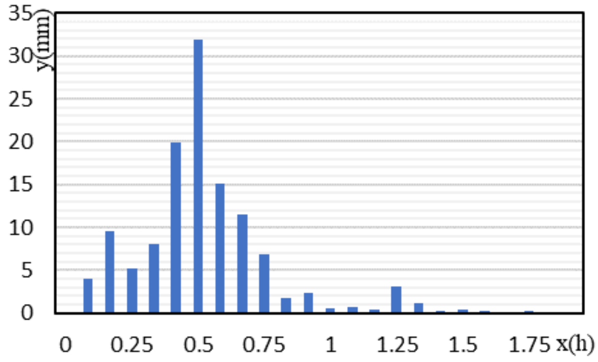


Fig.5. Two hours design rainstorm with the return period of 50 years

4.2 LID model and application in VR

4.2.1 3D Model Creation

Developing 3D Models is the initial step towards sponge city test site visualization. For this purpose, a 3D model was created of the land area surrounding Fengxi new town as follows:

(i) Lidar Digital Terrain Model extracted for the land around Fengxi new town.

(ii) High-resolution aerial imagery used for background landscape textures.

(iii) Autodesk Infraworks used to render a 3D model for Fengxi new town new area test site.

(iv) Buildings were derived from Lidar point classification

Further elements added to the model were:

(i) Features associated with urban environments, developed in Autodesk Maya, Sketchup including transportation, woodland and pedestrian.

(ii) GIS data layers representing current land use in Fengxi new town test site.

(iii) Simulated flood data layers to distinguish between planned design without LID and containing LID.

4.2.2 Terrain data, texture map and parameters

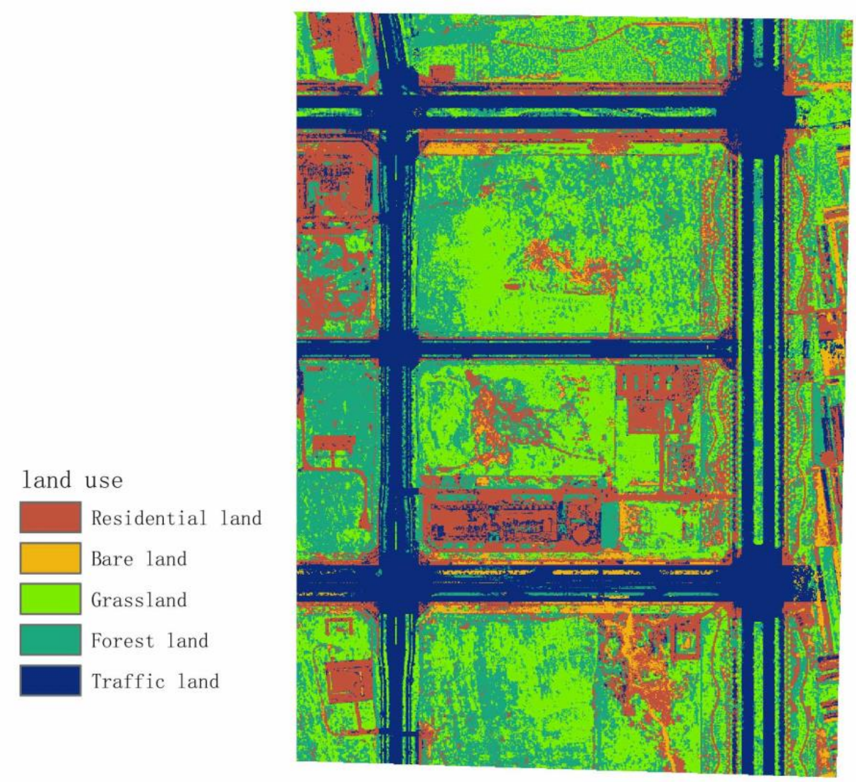


Fig.6. Land Use Classification

To ensure the accuracy of the simulation, the digital terrain data of the study area is captured with a resolution of 1m. Based on the orthophoto map, five types of land use (forest land, grassland, bare land, traffic and residential land) in the study area are shown in Fig.6. The surface texture map is obtained from Unmanned Aerial Vehicle (UAV) with a grid resolution of 6 cm. The Manning coefficient for each type of land use is determined according to reference data in the literature[42]. The infiltration rate for bare land, grassland and forest land is calculated based on actual measurement plus once a year drainage standard (LID not implemented) and actual measurement plus once in three years drainage standard (LID implemented). The infiltration rate for residential land and roads only rely on drainage system which is based on once in three years or once a year drainage standard (LID implemented or not).

Table 3 Land Use types, surface infiltration rate and manning coefficient

Land Use Classification	Area (km^2)	Percentage (%)	Manning Coefficient (n)	Infiltration rate (mm/h)	
				Without LID	LID
Residential	0.2	28.09	0.015	10.47	77.7
Bare land	0.022	3.09	0.030	149.26	216.49
Grassland	0.19	26.69	0.060	55.5	127.77
Forest Land	0.21	29.49	0.200	120.86	188.09
Traffic Land	0.09	12.64	0.014	10.47	77.7

According to the Fengxi new town rainstorm formula, when the rainfall intensity is greater than 10.74 mm/h, soil infiltration and the pipe network will be unable to remove all surface water and it will accumulate and cause surface runoff. The parameters taken for each land use type are shown in Table 3.

4.2.3 User Interaction Features

The user interaction interface has been developed to fit with the content and output of 3D model to be consistent with the purpose of use (Fig.7). It includes 3D icons ‘drag-and-drop’ module, design analysis module, 3D stereo panorama module, storyboards module and online shared view module. This part of the experiment focused on the interaction and usability of the interface, and the recognizability of the type of visualization. The 3D icons ‘drag-and-drop’ module allows participants to choose where they would like to position elements (trees, cars, characters, etc.). The 2D and 3D inundated area can be measured in the design analysis module. ‘3D stereo panorama’ module shares the VR experience as the weblink or QR code which provides 360° view of rendered panorama. Through the ‘storyboards’ module, a user will be guided on a prepared tour of specified features including a series of snapshot views or a dynamic, video pathway through parts of our sponge city 3D model. Online shared view module is also used to capture user/stakeholder comments of sponge city design plans.

Fig.7. User Interaction Features applied in Sponge City Design Plans

4.2.4 Stakeholder Workshop

Developed models are designed to be used in stakeholder and public engagement events to raise awareness of flood risk in the sponge city districts, and the additional identification of local issues associated with low impact development and sponge city construction. The workshop includes visualization tools set up, sponge city planning scenarios in VR, participants preferences and comments, and stakeholder analysis which is similar to other knowledge exchange activities[12][43]. The model is navigable, with interactivity to appeal across the range of prospective audiences. Drop-in interactive sessions of 30 minutes are planned to run throughout each day, with hand-held consoles used for providing feedbacks. Presenting audiences with scenarios of potential future flood mitigation measures and LID plans provides a basis for talking through opportunities, conflicts and the identification of new ideas for sponge city construction. Each session comprises:

i) Visual exploration of flood simulation and LID scenarios from different viewpoints

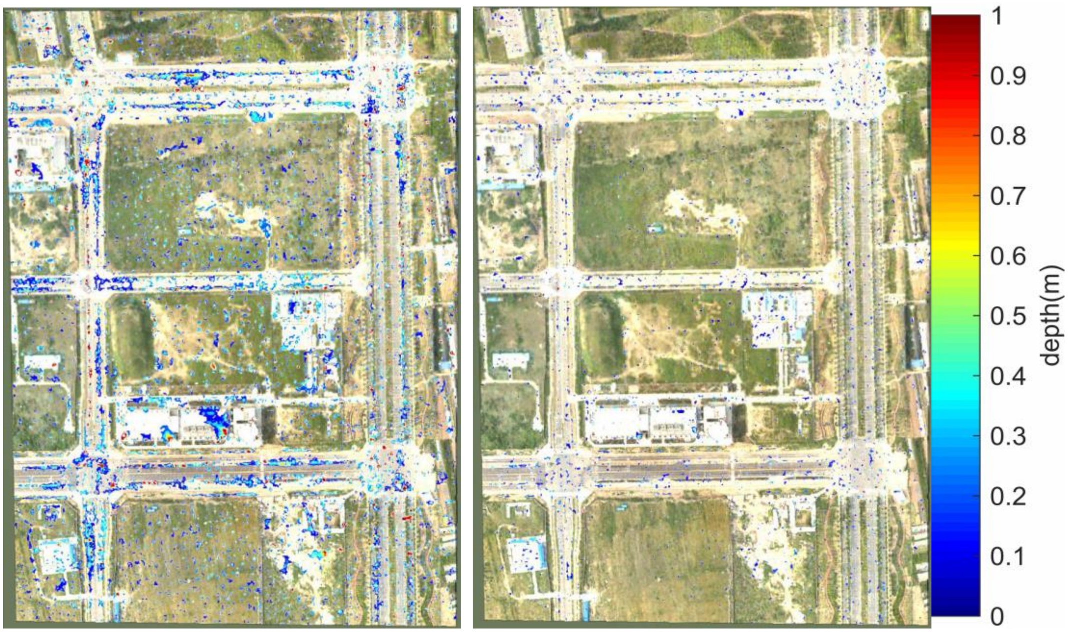
ii) Testing, audience understanding of key messages conveyed during the sessions.

iii) Interactive exploration and voting on options for addressing local sponge city issues

5. Results

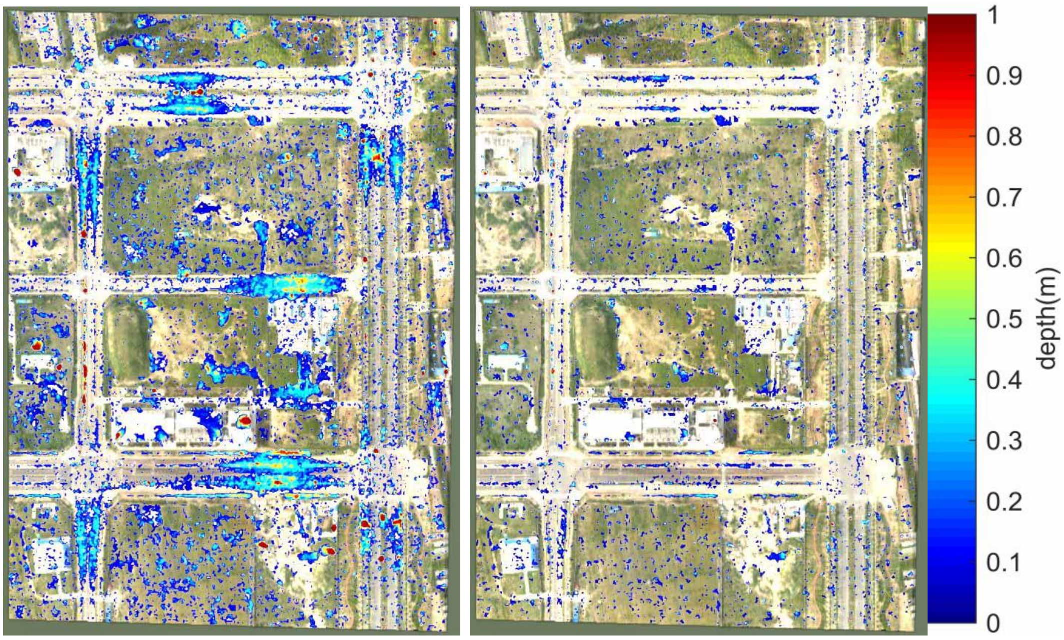
5.1 2D Simulation results with design rainstorm

Inundation maps show the combined effects of design rainstorm with different implementations of the LID approach as defined by varying input parameters. Comparing flood simulation without LID and with LID from the return periods of both 10 years (Fig.8) and 50 years (Fig.9), shows the considerable ‘sponge’ effect of the LID reconstruction for Xixian New District by reducing surface water flooding in the urban environments, especially for the more extreme (1 in 50 year) event.



t=1h, without LID t=1h, LID

Fig.8. Flood inundation map with the return period of 10 years in Fengxi new town



t=2h, without LID t=2h, LID

Fig.9. Flood inundation map with the return period of 50 years in Fengxi new town

5.2 Flood simulation and LID scenarios in VR

A prototype VR model provides the user with overlaid data relevant to the viewer's location and field of view. In addition, an online model is used to display 3D environment integrated with spatial analysis data and other water data. This online model also serves to capture user/stakeholder comments that they associate with surface water or water retention/infiltration features and therefore to facilitate collaborative interaction based upon the design simulation results for Fengxi new town VR model.

Extra elements have been added according to participants requirements (trees, cars, characters, etc.). Fig.10 and Fig.11 show the Fengxi new town VR model with simulated flood events before and after LID with 10-year and 50-year return period.

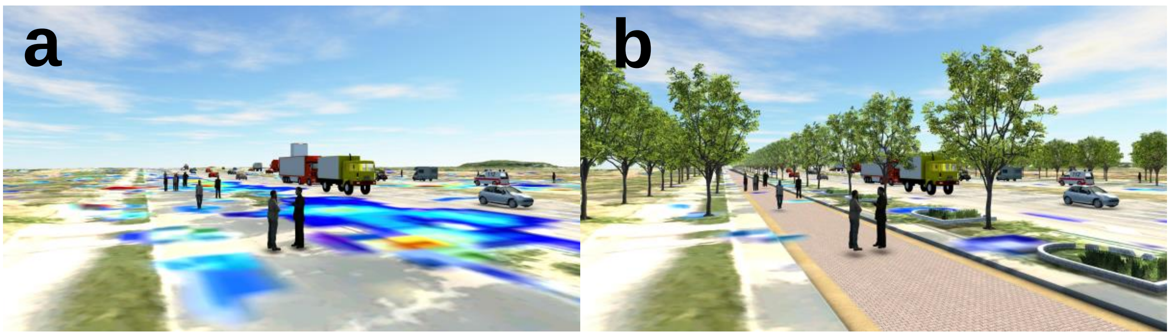


Fig.10. Visualize flood events in 3D virtual Environments in Qinhuang Avenue of Fengxi new town with 10-year return period: (a) t=1h, without LID; (b) t=1h, LID.

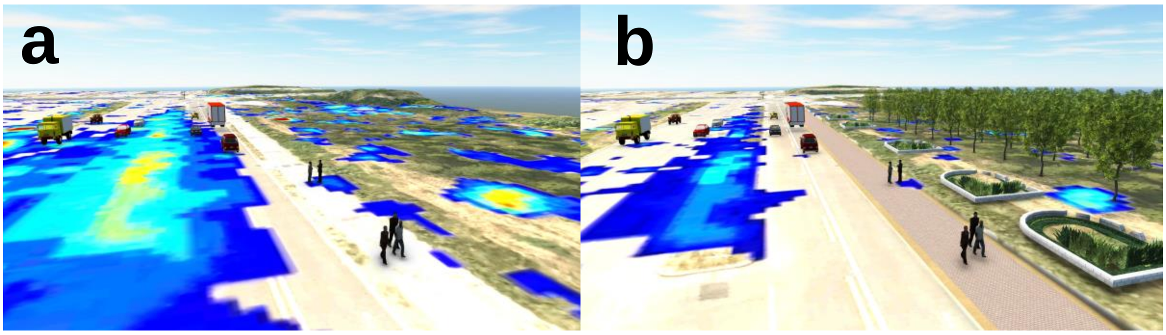


Fig.11. Visualize flood events in 3D virtual Environments in Fengjing Road of Fengxi new town with 50-year return period: (a) t=2h, without LID; (b): t=2h, LID.

In Fig.12, the LID scenarios of Fengxi new town in VR model are presented. In addition to the roadside vegetation, the associated buildings with greenroof for intercepting rainwater and helping to mitigating the urban heat island effect are visible. There is a close view of 3D model of rain garden and permeable pavement in Fig.12b. Underground pipe corridors implemented in LID approach (Fig.13a) illustrate how pipe design planning not only eliminates problems of various cables in the air but also improves urban landscape, intensively utilizes urban underground space.

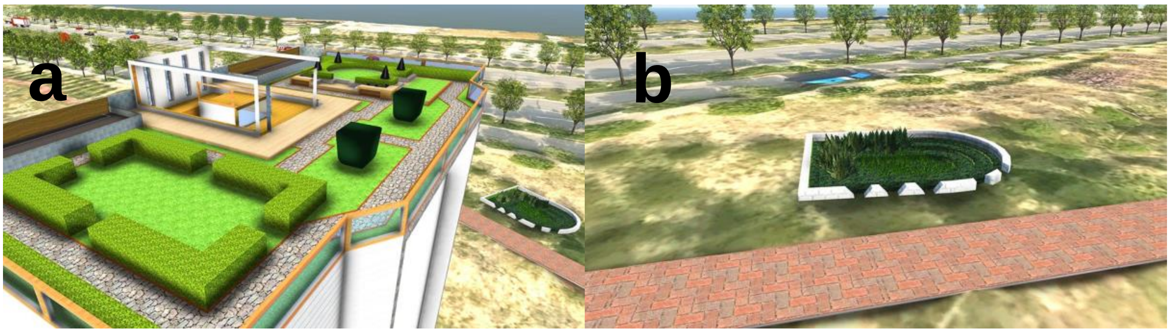


Fig.12. Fengxi new town LID scenarios in VR: (a) Green roof; (b) Rain Garden and Permeable Pavement

With the aid of the 360-panorama functionality of VR model, users are able to access all 360° of the viewscape of the LID scenarios with panoramic images and interactive virtual view. In order to facilitate immersive view, VR headset devices (Fig.13 (b)) are used to test audience perceptions and reactions.

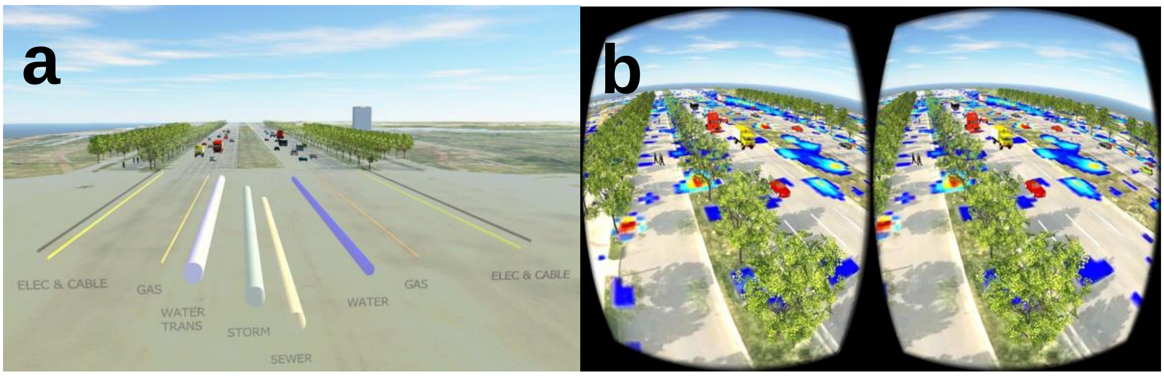


Fig.13. (a) Fengxi new town underground pipe corridors design in VR; (b) Immersive display simulated flood event in Fengxi new town with Oculus Rift

For effective stakeholder engagement, it is important to provide sufficient detail of features to enable participants to be able to identify and locate themselves with respect to a planned development. The level of detail (e.g. number of features, and the visual detail with which they are presented) has been tested in a workshop with key stakeholders (e.g. sponge city planners) and representative members of the public (e.g. local communities public).

The responses to the proposed questions are listed in Table 4:

Table 4 Participant preference for integrated simulation and 3D visualization in sponge city construction

Question	Yes	No	Neutral
Is 3D visualization most suitable for improving the communication and consultation process within the sponge city development?	15	5	0
Do you think 3D visualization is better for showing LID scenarios rather than 2D visualization?	16	3	1
Do you think integrated simulation and 3D visualization is more suitable for decision -making support of flood risk management in sponge city?	18	1	1

The preference rating for decision-making support of flood risk management is very high because the visualization of flood propagation and simulation of areas of surface water accumulation is considered practical and beneficial in terms of making effective response plans and providing detailed visual evidence.

Audience feedback suggested that the virtual environment was very effective in providing a more realistic impression of the different layouts and characteristics of the LID approach in sponge city construction, as compared to conventional 2D planning images, and that they enabled comparisons to be made of the differences in the expected outcomes of the alternative simulated flood events. This suggests considerable added value from using the 3D visualization to communicate the relationship between LID design features and the resultant reduction in risk in the context of participatory spatial planning.

6. Discussion and Conclusion

In this paper, actual and design flood events in pilot sponge city have been simulated and integrated with a 3D VR environment. In addition, urban development scenarios have been applied into sponge city construction using design plan both with and without LID in VR.

The integrated simulation and visualization platform has provided a procedure for constructing realistic urban environments that incorporate flood design features and monitoring of their performance during extreme rainfall events. Through the flood simulation model, it is possible to predict where the flood may have occurred, how serious it would be, and how different mitigation measures may affect flood risk in different situations. The simulation model can also identify areas of surface water accumulation and their hydraulic relationship to the dynamics of different rainfall return period events. This includes the effects on urban stormwater processes both before and after LID is carried out which is especially useful for decision makers to help identify the most effective features of LID design in reducing surface runoff.

3D visualization was integrated at different stages throughout the process of sponge city planning which includes scenarios of LID design, flood risk, vegetation creation and integrated pipe systems. For LID design, the visualization is able to provide an interactive 3D model of rain gardens and permeable pavement at different scales which can be shared with individuals and in collaborative groups to enable feedback through online comments. Woodland creation in sponge city is presented by adjusting woodland area, mixing tree species and changing tree density through 3D virtual environment in order to choose the best woodland planning scenario. Our 3D flood risk model offers not only numerical data or graphical output, but has been identified from user feedback to also provide more useful and appealing 3D visual information. It can handle dynamic flood behaviour and predict inundation areas in real time which is important for flood warning and for disaster risk planning scenarios. 3D reconstruction of underground pipelines has been implemented to help understand their role in implementing an integrated spatial design relative to surface features, which is not easily apparent in 2D media. This also provides effective technical support for the planning and construction of underground pipelines, integration of pipe corridors into sponge cities, rational use of underground space, and safeguarding of pipelines. With the help of interactive 3D visualization tools, the extent of flooding combined with other features such as co-benefits of the design can be better viewed and understood, as also assisted by 360º VR panorama, by which users can access a ‘bird’s eye’ interactive view of sponge city development plan.

Results are being used to inform the design of tools for eliciting stakeholders and public responses to prospective changes in flood risk management in urban and peri-urban environments, including development of LID scenarios and flood events visualization. The enhancement of user interaction through VR has potential implications for the planning and design of sponge city to increase the effectiveness of their use, and contribution to wider green infrastructure. Community recognition of potential multiple benefits from LID in sponge city such as improving urban drainage system and reducing urban waterlogging, supports the aims of the sponge city policy in respect of building ecologically-based drainage facilities, decreasing urban runoff pollution and protecting urban ecological environment.

The importance of adapting design concepts to local conditions is a key premise of sponge city planning and a crucial step in developing quantitative analysis in terms of scheme performance and resilience during extreme rainfall events. Our work in the pilot study areas suggests there are further steps that should also be considered in advancing integrated simulation-visualization platform:

(i) In order to improve the prediction accuracy of the urban flood simulation, high-resolution terrain data, as obtained by UAV, should be sought.

(ii) The further integration of building information modeling (BIM) and GIS applications in urban planning should be promoted, such as through municipal pipe network management, underground integrated pipe design, residential community planning, existing building renovation, operation and maintenance management, etc. Combined data can be used to improve modeling accuracy, analysis accuracy, decision efficiency, and cost control.

(iii) In addition to user interaction through a dedicated VR platform, the development of software for use with mobile devices (e.g. phones, laptop computers and tablets) appears likely to continue, exploiting increased computational capabilities of hardware and communications networks in flood risk management. An extension of Apps on mobile devices is the use of low-cost Virtual Reality headsets. These are likely to be used increasingly for early engagement with stakeholders for discussion about plans for sponge city construction in Xixian new area or eliciting ideas for potential LID scenarios.

(iv) An additional feature of the integrated simulation-visualization approach is that it can facilitate a cross-scale approach by zooming between local neighbourhood district detail and city-level planning. The requirement to integrate between scales has been recognized as a key deficiency in current sponge city design implementations[9], and further development of visualization level-of-detail implementations at different scales could be used to help address this issue.

Existing and planned future developments show there are good prospects for using interactive sponge city models to integrate georeferenced monitoring data from multiple sources through the use of combined GIS-VR platforms, which can also provide a crucial collaborative step in converting planning documents into a practical reality. In this way, interactive visualization becomes the key step in refining the initial design concept for the sponge city into a shared learning experience through which flood risk management can be better integrated with the wider range of issues that influence urban wellbeing.

Acknowledgments

This research was supported by the open fund grant from State Key Laboratory of Eco-hydraulics in Northwest Arid Region, Xi'an University of Technology (Grant No. 104-206071712); Scottish Government RESAS Research Programme; National Key Research and Development Program of China (Grant No. 2016YFC0402704); National Natural Science Foundation of China (Grant No. 19672016) and Research Program of Sponge City at Xixian New Area, China (Grant No. 104/441216042).

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